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Assessment of the vulnerability of a coastal freshwater system to climatic and non-climatic changes: A system dynamics approach

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ABSTRACT

Water resources management faces many challenges in coastal areas of developing countries, where climate change coupled with high rates of population growth and urbanization have the potential to cause severe water scarcity. Of particular concern, are sea level rise and altered precipitation regimes that will influence spatial and temporal patterns of river discharge, water levels and saltwater penetration in estuaries. A sound understanding of factors affecting the vulnerability of coastal freshwater systems is therefore needed to mitigate the potential impacts of climatic and non-climatic changes. In this study, a system dynamics modeling approach was employed to explore the vulnerability of the coastal freshwater system in Da Do Basin, Vietnam to projected sea level rise, upstream flow decline and socio-economic development. This system includes the Da Do River and irrigation channels that receive freshwater through sluice gates from the Van Uc and Lach Tray rivers. The model was developed as a learning tool for decision-makers to improve their understanding of the spatial and temporal dynamic behaviors of the system and to inform adaptation decision-making by allowing exploration of plausible future scenarios. The model was developed, calibrated and validated using both historical data and expert knowledge elucidated via stakeholder consultation. Model results indicate that under current conditions, freshwater availability is sufficient to meet existing domestic, industrial and agricultural demands. However, the coastal freshwater system changes significantly and collapses under several plausible future scenarios. Future projections suggest that declining upstream flows will be the strongest threat to the system's vulnerability. System dynamics models enable consideration of the interactive effects of a range of climatic and non-climatic drivers on water resources availability thereby facilitating improved planning for collective and proactive adaptation actions to efficiently secure freshwater resources to support socio-economic development of coastal basins in the face of climate change.

1. Introduction

Coastal freshwater supply and demand systems comprise a wide range of complex natural and anthropogenic processes involving multiple interactions between interdependent components with many feedbacks. Water supply is particularly affected by climate variability and climate change with sea level rise, and altered precipitation regimes (IPCC, 2013) influencing temporal and spatial patterns of river discharge, water levels and saltwater penetration along estuaries (Nguyen et al., 2008). Changes to upstream flow regimes, for instance, can have a substantial impact on regional water resource and seasonal water supplies in downstream areas (Zhou et al., 2017). Rising salinity levels in rivers due to both sea level rise and declines in upstream flows can degrade surface water supplies and impair the agricultural, industrial and urban systems which rely on them (Nguyen and Umeyama, 2011). Spatial and temporal variation in water and salinity levels driven by tide level and upstream flows often necessitate spatial and temporal changes to the operation of sluice gates along estuaries which supply freshwater to agriculture, industry and households (Nguyen et al., 2012). In contrast to water supply, water demand is driven largely by population growth, economic development and land use change

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(Sušnik et al., 2013). The interactions among these drivers are widely considered to be the main factors contributing to a growing gap between water supply and demand in many locations around the world (Dawadi and Ahmad, 2013). Water scarcity is especially prevalent in coastal areas of developing countries, where high rates of population growth and urbanization are typical.

Overall, the vulnerability of coastal freshwater systems over time is determined by changes in these major climatic and non-climatic factors. Understanding the dynamic balance of coastal water supply and demand systems therefore relies on knowledge of the temporal and spatial variations in these drivers as well as their interactions. Dynamic simulations of water supply and demand systems provide an opportunity to investigate the vulnerability of these critical systems to scenarios that combine projected climatic and non-climatic changes. Such a holistic understanding of the temporal interactions among interdependent elements in complex systems leads to more effective learning and management (Winz et al., 2009), as well as assisting consensus building in the identification of robust adaptation options which address both current and future conditions (Füssel, 2007). System dynamics (SD) modeling thus provides an ideal approach for understanding complex and dynamic water supply and demand systems to inform critical management decisions (Sahin et al., 2015).

Here, we demonstrate an SD modeling approach to assessing the vulnerability of a coastal freshwater system in the Da Do Basin in Hai Phong, Vietnam under current conditions, and with respect to projected climatic and non-climatic changes over time. This basin is potentially highly vulnerable to climate change impacts due to its coastal position and its high rate of population growth and urbanization (DONRE, 2015). The basin features a sluice gate system that supplies freshwater to the Da Do River and irrigation channels as well controlling salinity ingress from the neighboring Van Uc and Lach Tray rivers. Consequently, the Da Do Basin provides an opportunity to investigate the effects of different operational responses (i.e. spatial and temporal variation in opening and closing of sluice gates) to changing climatic and non-climatic conditions.

An SD modeling approach was used to investigate interactions and feedbacks between tide level, river flows, salinity, water level, population growth, and industrial and agricultural production in the coastal freshwater system in this basin. The model was then used to assess the vulnerability of the sluice gate system to understand how potential relative sea level rise, reduced upstream flows and salinity penetration might alter long-term freshwater supplies and affect subsequent management of the system. Effects of changes in water demand due to population growth, and changes in industrial and agricultural production in the basin were also considered.

The specific objectives of this study are to: (1) enhance understanding of the dynamic behavior of this coastal freshwater system as it responds to spatial and temporal changes in its key climatic and non-climatic drivers and; (2) analyze plausible future scenarios to identify which factors and interactive effects are likely to be the most damaging to the vulnerability of the coastal freshwater system. Ultimately, the SD model was developed to provide a learning tool for local stakeholders to inform adaptation decision-making.

2. Case study context

The case study for the SD modeling is the Da Do Basin in Hai Phong, a coastal city in the Red River Delta in northern Vietnam. The Da Do Basin is the largest area of the city (Fig. 1) with a population of 605,000 people and an average population density of 1075 people/km^2 (HPSD, 2015). The basin provides freshwater for five districts in Hai Phong (An Lao, Kien Thuy, Kien An, Duong Kinh and Do Son). An annual population growth (1%), coupled with high rates of industrialization and urbanization are expected to lead to water shortages, possibly constraining socio-economic development for the coastal city over coming decades (DONRE, 2015).

Hai Phong city is a flat and low-lying area with a mean elevation of around 1–1.5 m above sea level (DONRE, 2015). Consequently, tidal influences extend a considerable distance inland. In the Van Uc and Lach Tray estuaries (Fig. 1), seasonal hydrological patterns depend on both riverine and marine conditions and are therefore shaped by seasonal precipitation, river flows and tide level. Analyses of climate data from National Northeast Meteorological and Weather Stations (NNMWS) indicate that the lowest monthly downstream flows and rainfall over fifteen years from 2001 to 2014 occur during the dry season, between December and May. As a result, the highest salinity levels and lowest water levels typically occur during this period, thereby causing a high potential for water

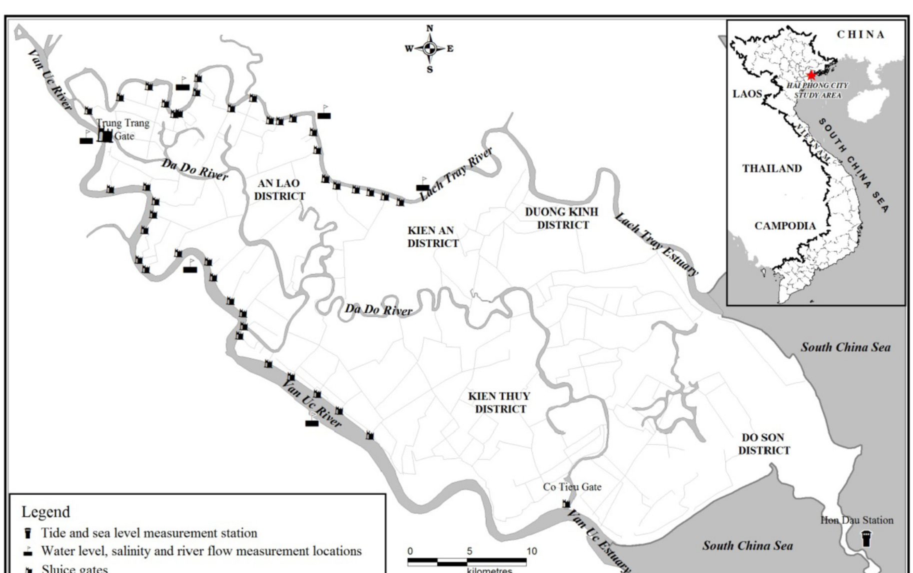

Fig. 1. Da Do basin, Hai phong city, Vietnam.

Table 1
Sluice gate flow capacities and ranges along the Van Uc and Lach Tray rivers.

Van Uc River			Lach Tray River		
Sluice gate	Flow (m^3/s)	Range	Sluice gate	Flow (m^3/s)	Range
Trung Trang	139.28	Range I	Goc De	3.94	Range I
Tan Hung	6.89	30 to 40 km	Thuong Trang	3.05	32 to 40 km
Tao	4.13		Cau	14.47	
Ngo	4.13		Hang La	2.54	
Nghe	4.57		Hoa Dai	6.89	
Muoi	5.17		Song	3.55	
Cat Tien I	3.05	Range II	Do Lai	5.17	
Cat Tien II	5.08	20 to 30 km	Hoa Giang	5.86	Range II
Cau Dong	3.55		Don Cung	6.89	24 to 32 km
Cam Van	6.89		Dong Sim	1.47	
Truc Dao	5.08		Tay	5.51	
Bach Cau	5.17		Chi Lai	3.05	
Canh Tay	4.13		Bai Nuc	1.31	
Ham Long	6.89		Bai Vet	5.17	
Dai Dien	2.94		Tham Len	3.05	Range III
Cong Dun	3.05		Den Cuu	1.47	20 to 24 km
Kim Con	30.47	Range III	Lo Gach	1.63	
Cong Hau	5.17	15 to 20 km	Truong Son I	3.45	
Phuong Ha	5.17		Truong Son II	26.12	
Cao Mat	5.17		Ca So III	3.45	
Mai Duong	6.53				

shortage in the basin, from December to May (DONRE, 2015).

The Da Do Basin is bounded by the Van Uc and Lach Tray rivers, both of which connect directly to the sea and therefore, contain tidal waters that move upstream to meet freshwater flowing downstream. There are 21 and 20 sluice gates (Pham, 2014) along the Van Uc and the Lach Tray rivers, respectively (Fig. 1). These sluice gates supply freshwater from the Van Uc and Lach Tray rivers to the Da Do River and its connected irrigation channels. The Trung Trang gate is the largest gate in the system and controls the main freshwater input to the Da Do River (Table 1). The other sluice gates are much smaller and provide freshwater for irrigation channels only. The Da Do Irrigation Management Company has divided these gates into three ranges (Table 1) based on measurement locations of water level and salinity as well as similarity of topography in each range (Pham, 2014).

The Da Do River begins at the Trung Trang sluice gate and ends at the Co Tieu sluice gate in the estuary. The Co Tieu sluice gate remains closed most of the time to retain freshwater and prevent saline penetration, only opening during storms or heavy rain to protect the river banks. The irrigation channels on either side of the Da Do River also have sluice gates to retain freshwater and similarly release water into the Van Uc and Lach Tray rivers when necessary.

Water management in this region faces challenges due to sea level rise (Fig. 2), declining precipitation (Fig. 3) and increasing temperatures (Fig. 4) which together alters river flows, water levels and saltwater penetration in the estuaries, especially during the dry season, affecting freshwater availability in the Da Do River and the irrigation channels.

3. Methods and model development

3.1. System dynamics modeling approach

System dynamics modeling was developed to study the behavior of complex systems and interactions among multiple, disparate external factors in situations where stocks and flows are fundamental and capture time delays and internal feedback loops that alter system behavior (Sterman, 2000). A SD model comprises three main components: stocks (e.g. freshwater availability in the Da Do River and irrigation channels); flows (e.g. water flows through sluice gates) and converters which control flow rates (e.g. salinity and water levels). Converters link the system elements and create feedback loops which are the basic structural elements of dynamic systems, reflecting a chain of causal relations among the interacting components of a system (Sterman, 2000).

The first step in any SD modeling project is to understand the system and determine the system boundary to develop a model structure which comprises positive and negative relationships between variables, feedback loops, system archetypes and delays (Sterman, 2000). Subsequently, an initial working simulation model is constructed which is then modified and improved iteratively to obtain the desired level of detail and complexity, and to

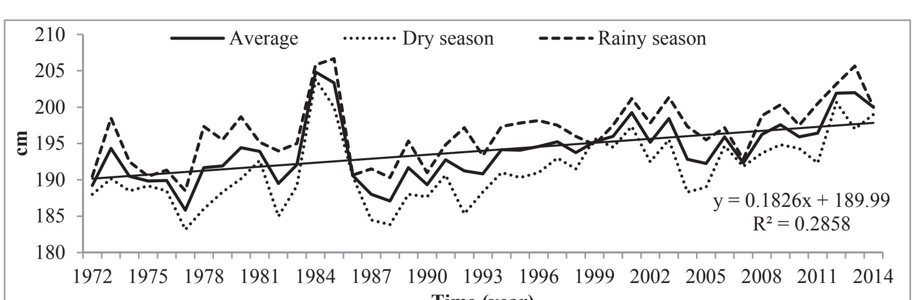

Fig. 2. Average sea level in Hai Phong over a 43 year period (Source: NNMWS, 2015).

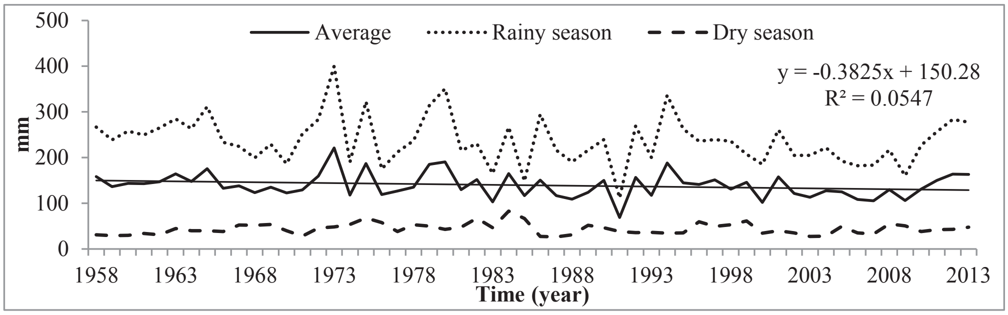

Fig. 3. Average precipitation in Hai Phong over a 57 year period (Source: NNMWS, 2015).

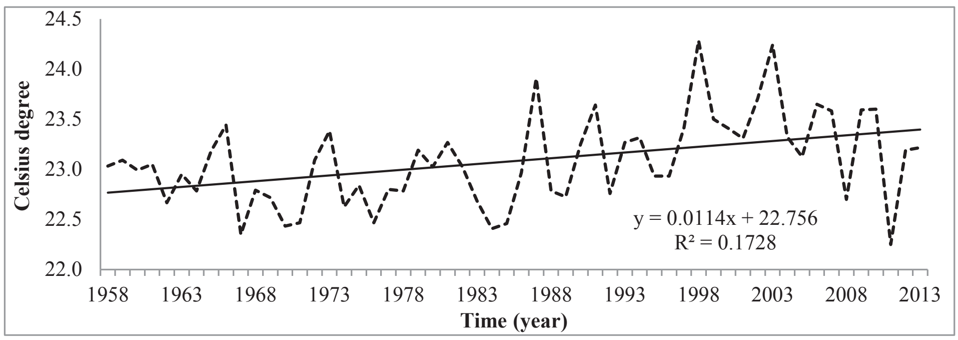

Fig. 4. Average temperature in Hai Phong over a 57 year period (Source: NNMWS, 2015).

closely mimic the real system under investigation to the required level of accuracy (Sušnik et al., 2012).

SD modeling incorporates continuous and discrete time concepts to deal with changes over time (Sterman, 2000). In addition, the SD modeling approach facilitates an understanding of complex systems by incorporating, simulating and analyzing biophysical, hydrological and socio-economic components in one comprehensive model (Sahin et al., 2017).

3.2. System dynamics modeling approaches in water supply and demand systems

SD modeling has been applied in water resource management around the world (Winz et al., 2009). SD models provide a valuable strategic tool for modeling water supply and demand because they facilitate an understanding of the dynamic, complex and multi-dimensional nature of water supply and demand management that can be used to assist forecasting, infrastructure planning, demand planning, and revenue and expenditure estimation (Sahin et al., 2015). SD models provide a holistic framework that allows modelers to understand interactions between hydrologic systems and socio-economic development. Numerous scenarios of both climatic and non-climatic drivers can be incorporated into one comprehensive model to explore outcomes through an adjustable dashboard display. The SD modeling approach has previously been applied in a range of management situations for water supply and demand (Appendix A). Few previous studies, however, have considered multiple interacting climate change drivers (.e.g. sea level rise and upstream flow decline) in combination with socio-economic factors acting on water supply and demand systems in estuaries.

3.3. Model development

The steps in development, calibration and validation of the SD model are shown in Fig. 5. Determining a model boundary is particularly important in identifying key system variables and specifying which variables are stocks or flows. In this study, key variables for simulation were chosen based on a combination of consultative workshops with 35 stakeholders (e.g. local water and climate change experts, decision makers, water resource managers and water resource users) in Hai Phong City in 2015, a review of the local context and analysis of historical data related to coastal water supply and demand. The most important variables influencing the balance of water supply and demand, identified through these approaches, were then incorporated into the SD model to assess the vulnerability of the sluice gate and freshwater storage system of the Da Do Basin under future climatic and non-climatic changes. The complete model was developed using Vensim DSS v.63 software package (Ventana) and it comprised two linked sub-section models: (i) a water level and salinity level sub-section model, and (ii) a sluice gate, freshwater storage system and water demand sub-section model (Figs. 6 and 7). Hourly data (total of 4368 h) from a six month dry season from December to May 2014 were used to assess the current balance of the coastal freshwater system in the Da Do Basin. Hourly time steps were used to capture temporal changes in tide level, water level and salinity and their influences on spatial and temporal opening of the sluice gates along the Van Uc and Lach Tray rivers.

Water supply to the basin is driven by water and salinity levels at each relevant location along the Van Uc and Lach Tray rivers as well as by water level in the Da Do River and irrigation channels. In turn, water and salinity levels in the Van Uc and Lach Tray rivers are strongly driven by interactions between upstream flows and tide level (Fig. 6). Increased tide level leads to an increase in water level

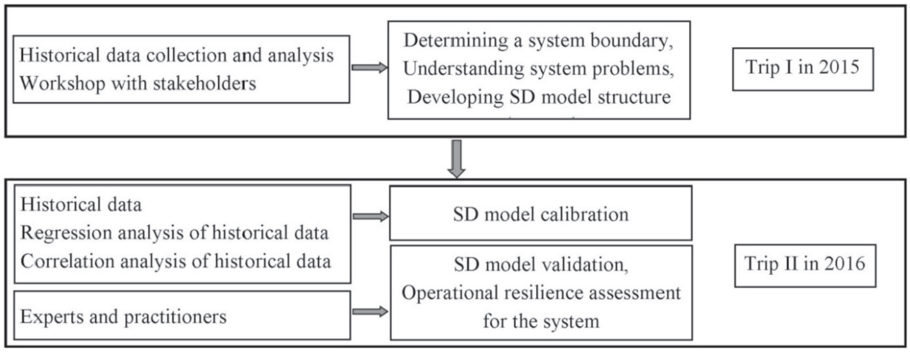

Fig. 5. A conceptual framework for the system dynamics model development, calibration and validation.

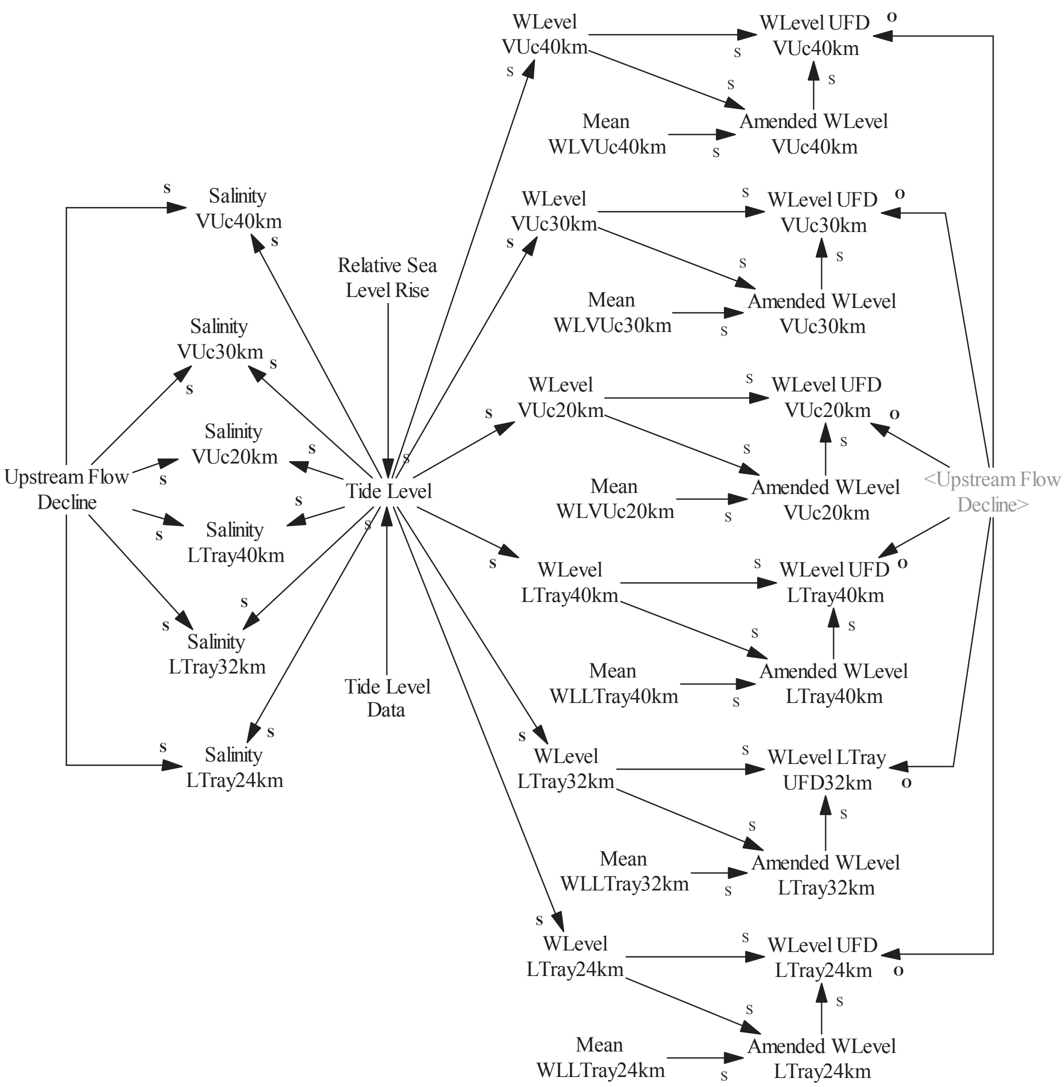

Fig. 6. Interactions of upstream flows and tide level spatially and temporally affecting water level and salinity along the Van Uc and Lach Tray rivers sub-section model *Note: S denotes same direction, O denotes opposite direction; UFD: Upstream flow decline, WL; Water Level, VUc: Van Uc River, LTray: Lach Tray River.*

and salinity along the Van Uc and Lach Tray rivers. Increased upstream flows result in higher water levels but a decline in salinity in these rivers. Tide level is expected to increase through time due to sea level rise (Fig. 2). Upstream flows, however, are declining due to reductions in precipitation (Fig. 3) and flow management for hydropower generation upstream (DONRE, 2015). Therefore, interactions between shifting upstream flows and tide level can be expected to generate further changes in water level and salinity level along the Van Uc and Lach Tray rivers.

Freshwater inflow through the sluice gates in this system is

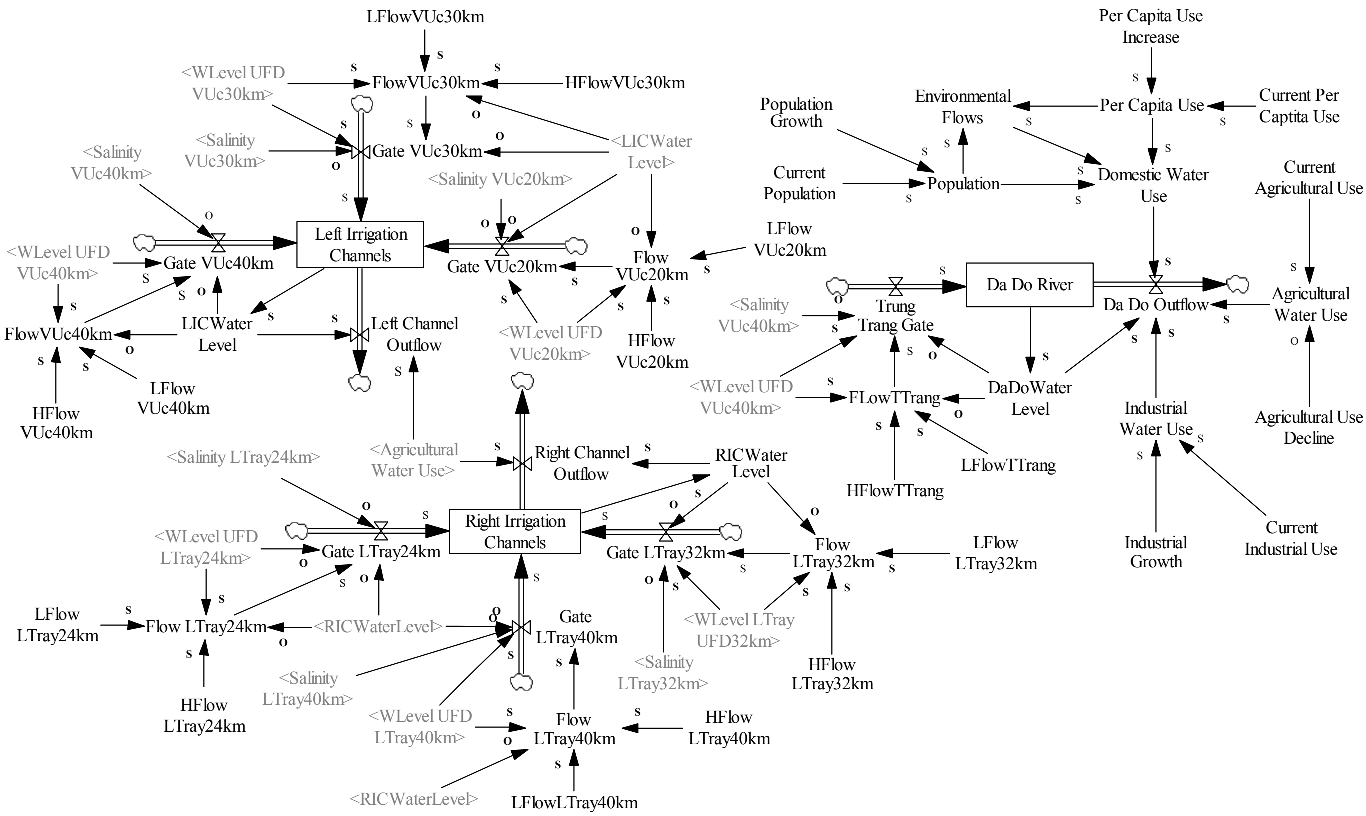

Fig. 7. Sluice gate, freshwater storage system and water demand sub-section model. *Note: S denotes same direction, O denotes opposite direction; UFD: Upstream flow decline, LFlow: Low Flow, HFlow: High Flow, RIC: Right Irrigation Channels, LIC: Left Irrigation Channels.*

limited by salinity level and water level in the Van Uc and Lach Tray rivers (Fig. 6) as well as water level in the Da Do River and irrigation channels (Fig. 7). Freshwater supply to the Da Do River and irrigation channels is also influenced by the operational capacity of the sluice gates (Fig. 7). Da Do Irrigation Management Company operates the sluice gates in strict accordance with regulations (Pham, 2014). Sluice gates will be opened if three conditions are satisfied: (1) water level in the Van Uc or Lach Tray rivers must be more than 276 cm, (2) salinity level in these rivers must be less than 1 part per thousand (ppt), and (3) water level in the Da Do River or the irrigation channels must be less than 280 cm.

Water demand is driven by a combination of domestic use and agricultural and industrial production at any point in time (Fig. 7). Domestic and industrial uses of water in the Da Do Basin are anticipated to increase over time because of population growth and increasing industrial production. However, agricultural water use is likely to continue to decrease over time as agricultural land is converted to industrial and residential land (DONRE, 2015).

3.3.1. *Data sources for model development and calibration*

Historical datasets were used to develop and calibrate the SD model (Table 2). Water level and salinity at six different locations were measured hourly to capture the impact of hourly changes in tide level on water level and salinity. Sea level, tide level and water level were measured relative to the National Height Datum.

3.3.2. *Scenarios for assessing system vulnerability*

Five future scenarios and changes in key data inputs (Table 3) were developed to investigate the vulnerability of the sluice gates and freshwater storage system under projected changes for the year 2050. Simulations targeted the year 2050 because it provides a long-term perspective from which the long-term dynamic behavior of the basin and the consequences of the future scenarios can be assessed.

The population of Da Do Basin was around 605,000 in 2014, with a mean annual growth rate of 1% between 2000 and 2013 (HPSD, 2015). A study by the Department of Natural Resources and Environment (DONRE, 2015) reported that water use for urban was 150L/person/day and rural areas was 100L/person/day in Hai Phong City. This study also estimated that by 2020 per capita water consumption for urban and rural residents would be 180L/person/day and 150L/person/day, based on the historical data and temperature projections in Hai Phong region. Over the past 57 years, from 1958 to 2014, average temperature in Hai Phong area has increased by 0.62 °C (Fig. 3). Temperature increase projections for the Hai Phong region in 2050, conducted by MONRE (2016) and based on the Fifth Assessment Report of IPCC in 2013, suggested that under RCP4.5, temperatures will increase by between 1.6 °C to 1.7 °C while under RCP8.5, temperature increases will be between 2.0 °C to 2.3 °C. Considering these data and the effects of water price, income and weather factors on per capita water consumption, per capita water consumption is calibrated at 120L/person/day currently and is assumed to be 180L/person/day in 2050.

Water consumption for major agricultural sectors (i.e. irrigation, livestock and aquaculture) was calculated based on the irrigation area, aquaculture area and livestock numbers between 2000 and 2014 as recorded in the Haiphong Statistical Yearbook (HPSD, 2015), together with available water consumption estimates (DONRE, 2015). Agricultural water demand was estimated to be 250,466,000 m3/year in 2014, and over the period 2004 and 2014, it decreased by about 0.5% per year. Therefore, a 0.5% per annum decrease in agricultural water use from current is assumed to

Table 2
Datasets for model development and calibration.

Data type	Period	Unit	Source
Sea level at Hon Dau National Station	Forty three years from 1972 to 2014	cm	NNMWS (2015)
Precipitation at Phu Lien Station	Fifty seven years from 1958 to 2014	mm	NNMWS (2015)
Tide level at Hon Dau National Station	Six months in the dry season, from December 2013 to May 2014	cm	VNASI (2015)
River flows at Trung Trang Station	Six months in the dry season, from December 2013 to May 2014	m^3/hour	NNMWS (2015)
Salinity	Six months in the dry season, from December 2013 to May 2014. Measured at six locations for both Van Uc and Lach Tray rivers	ppt	NNMWS (2015)
Water level	Six months in the dry season, from December 2013 to May 2014. Measured at six locations for both Van Uc and Lach Tray rivers	cm	NNMWS (2015)
Sluice gate inflow system	Inflow of each gate along the Van Uc and Lach Tray Rivers in the current system design, estimated based on water levels on both sides of the sluice gates	m^3/hour	Pham (2014)
Sluice gate opening schedule	Opening hours of each gate along Van Uc and Lach Tray rivers in the six month dry season, from December 2013 to May 2014.	hour/day	Pham (2014)
Freshwater storage system	Storage capacity of the Da Do River and Irrigation channel system in the current design	m^3	Pham (2014)
Population	Population of Da Do Basin in 2014	people	HPSD (2015)
Agricultural water use	Water use in the dry season from December 2013 to May 2014	m^3/year	DONRE (2015)
Industrial water use	Water use in the dry season from December 2013 to May 2014	m^3/year	DONRE (2015)
Per capita water use	Water consumption per person in 2014	Liter/person/day	DONRE (2015)

estimate agricultural water demand in 2050.

The industrial sector in Da Do Basin comprises three main categories: industrial zones, small industrial complexes and enterprises. Water consumption for each category was calculated based on the water use per category recorded historically from 2004 to 2014 (DONRE, 2015). Overall industrial water use in 2014 was thus estimated at 50,400m3/day with an average annual increase of about 2.5% from 2004 to 2014. Therefore, a 2.5% increase per annum from current was assumed to estimate industrial water use in 2050 (Table 3).

A relative sea level rise of 30 cm by 2050 (Table 3) was used in this study based on both historical data and sea level rise projections in Hai Phong region. Over the past 43 years, from 1972 to 2014, sea level at Hon Dau National Station in Hai Phong area rose about 20 cm (Fig. 2). Sea level rise projections for the Hai Phong region conducted by MONRE (2016), based on the Fifth Assessment Report of IPCC in 2013 that under the RCP4.5, sea level will rises by between 14 cm and 34 cm while under the RCP8.5, sea level increases by between 17 cm and 36 cm by 2050. A relative sea level rise of the upper range (30 cm) therefore sits well within these expected ranges under both storylines.

A relative sea level rise of 30 cm will produce an increase of 30 cm in the current tide level, and thus water level and salinity will also increase as a consequence. The lowest and highest levels of current tide level in the Hon Dau National Station (Fig. 1) are 30 cm and 370 cm, respectively (VNASI, 2015). Tide levels of 380 cm, 390 cm and 400 cm which will follow from the 30 cm relative sea level rise lay outside the range of the data available for calibrating the model. Water levels and salinity levels at these higher tide levels were therefore estimated by extrapolation using coefficient values obtained from simple linear regressions which link historical data on water level and salinity to tide levels (Appendix B) (e.g. salinity and water level at six locations on the Van Uc and Lach Tray rivers driven by tide level over time).

Scenarios for upstream flow decline (Table 3) were developed based on historical and projected precipitation in the Hai Phong region. Over the past 57 years, from 1958 to 2014, precipitation in the Hai Phong region decreased by between 5.8% and 12.5% (Fig. 3). Precipitation projections in the dry season for the upstream of Hai Phong as well as for Hai Phong region itself, produced by MONRE (2016). These projections indicated that under both RCP4.5 and RCP8.5 of the IPCC's Fifth Assessment Report of 2013 precipitation will have decreased by about 10% by 2050. Upstream flow decline leads to a decrease in water level and an increase in salinity level along the Van Uc and Lach Tray rivers. Predictions for decreased water level and increased salinity level were developed based on partial correlation analyses of historical data for (1) tide level at Hon Dau National Station, (2) river flows at Trung Trang station, and (3) water levels and salinity levels at six locations along the Van Uc and Lach Tray estuaries (Appendix C).

3.3.3. Model testing, sensitivity analysis and verification

In addition to directly incorporating historical data on water level, salinity, domestic water use and agricultural and industrial production in the six month dry season (Table 2) into the relevant variables in the SD model, the opening hours of sluice gates along the Van Uc and Lach Tray rivers were simulated to test the accuracy of the model. Opening hours of sluice gates are one of the most

Table 3
Scenarios and data inputs for assessing vulnerability of the sluice gate and freshwater storage system.

Variable	Current (2014)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Population (people)	605,000	+1%	+1%	+1%	+1%	+1%
Per capita water use (L/day/person)	120	180	180	180	180	180
Industrial water use (m^3/day)	50,400	50,400	+2.5%	+2.5%	+2.5%	+2.5%
Agricultural water use (m^3/day)	696,000	696,000	696,000	- 0.5%	- 0.5%	- 0.5%
Upstream flow	As water level at six locations	As current	As current	As current	*Note*	*Note*
Sea level (cm)	As tide level	As current	As current	As current	As current	+30 cm

Note: Decrease by 15 cm in upper level, by 30 cm in lower level for the Van Uc River; and decrease by 10 cm in upper level, by 30 cm in lower level for the Lach Tray River (see Appendix C for additional explanation).

important indicators of system performance because the gates can only be opened if relevant conditions for water level (on both sides of the gates) and salinity are all satisfied. Spatial and temporal changes in water levels and salinity along the Van Uc and Lach Tray rivers are strongly driven by tide level and upstream flows. The water level in the Da Do River and irrigation channels is driven by water usage by households, industrial and agricultural production.

The coefficient of determination (R^2) was used to assess agreement between observed data and simulated values of the opening hours of sluice gates. R^2 indicates the proportion of the variance in measured data explained by the model. The value of R^2 ranges from 0 to 1 with values closer to 1 indicating the model simulates the system well. R^2 is calculated as follows:

$$R^2 = \left(\frac{Cov(O,\ S)}{\sigma O\ \sigma S}\right)^2 \tag{1}$$

where O and S are the observed and simulated values of the variable of interest; Cov (O,S) is the covariance between observed and simulated values, and σO and σS are the standard deviations of the two sets of values (Safavi et al., 2015).

Sensitivity analysis was also performed to increase confidence concerning the dynamic behavior of the model and to evaluate the impact of parameter uncertainty on the water availability in the system. Sensitivity analysis also sought to identify which variables have the greatest impact on the dynamics behavior of the model, thereby guiding decision-making regarding future policy and management (Sušnik et al., 2013). Following the method proposed by Maani and Cavana (2007), this study examined the model's sensitivity to ±10% changes in individual internal variables (i.e. water level, salinity, and domestic water use, agricultural and industrial water demand) while holding other input variables constant at their base case values. The corresponding changes in freshwater volume in the system over the six month dry season were recorded as each internal variable was adjusted to identify which variables exerted the strongest influence on water availability in the system.

The SD model was further revised through consultation with twelve stakeholders including a climate change expert from the National Northeast Meteorological and Weather Stations, a socioeconomic statistician from Hai Phong Statistics Department, and managers and researchers from the Da Do Irrigation Management Company. Stakeholders were consulted about input data validity, relationships among variables and model logic. Consultation workshop participants agreed with model predictions and were confident that the model could be used to identify effective adaptation options under future scenarios.

4. Results

4.1. Model testing and sensitivity analysis

The results of model testing are shown in Table 4 and Fig. 8. The simulated results followed the same trend as the observed data, with the opening hours of sluice gates fitting well with observed data. Values of R2 (Table 4) range from 0.78 to 0.93 indicating that model replicates the opening hours of sluice gates very closely. This is, especially true for the model's ability to predict opening hours of the Trung Trang gate (R2 = 0.93), the most important gate for controlling water supply in the system.

The somewhat lower value of R^2 for the sluice gates along the Lach Tray River could be due to high levels of uncertainty driven by the high complexity of this section of the system (e.g. local precipitation, water level and salinity as well as operational management of sluice gates). However, this is not a major concern because the aim of the SD model is to understand dynamic behavior patterns of the system over time rather than to make accurate predictions of system variables (Sterman, 2000).

The results of sensitivity analysis for freshwater storage balance are shown in Fig. 9. Water level and salinity had the strongest influence on the freshwater storage balance in the system. According to criteria proposed by Maani and Cavana (2007), freshwater storage balance was highly sensitive to changes in water level (>35% change), and moderately sensitive to changes in salinity (15–34% change), whereas the sensitivity of freshwater storage balance to changes in agricultural water use, domestic water use and industrial water use were low (5–14% change).

4.2. Changes in freshwater storage balance under future scenarios

Model results for current conditions indicate that existing operation of the sluice gates and the freshwater storage system satisfies water demand from domestic, agricultural and industrial water uses. The current availability of freshwater in the system is about 19 million m^3/hour (Fig. 10). This water availability is considered to be business as usual (BAU) and can be contrasted with freshwater availability in the system under the five mixed scenarios for 2050 (scenarios in Table 3, results in Fig. 10). Water availability falls below BAU, and is insufficient to meet domestic, industrial and agricultural water demand in the latter months of the dry season under the examined scenarios of population growth and increased per capita water use (Scenario 1), increased industrial production (Scenario 2) and declining agricultural use (Scenario 3). Furthermore, when upstream flow decline (Scenario 4) also occurs, the freshwater storage system essentially collapses. However, if a relative sea level rise of 30 cm (Scenario 5) is also introduced, the system only collapses in the later months of the dry season (Fig. 10).

4.3. Salinity and water level under upstream flow decline and sea level rise

To better understand outcomes under Scenarios 4 and 5, water level and salinity along the Van Uc and Lach Tray rivers were simulated under BAU, upstream flow decline (UFD), and upstream flow decline and relative sea level rise in combination (UFD & SLR). Upstream flow decline and relative sea level rise change the water level and salinity along the Van Uc and Lach Tray rivers, leading to temporal and spatial changes in the opening hours of the sluice gates along these rivers. The scenario analyses show that upstream flow decline leads to a decrease in river water levels and an increase in salinity along the Van Uc and Lach rivers. As a result, sluice gates located within 20 km and 24 km of the mouths of the Van Uc and Lach Tray rivers are completely closed because salinity is too high (Table 5). However, the increase in salinity is not sufficient to affect opening of the sluice gates more than 30 km from the river mouths

Table 4
Coefficient of determination for observed against simulated opening hours of sluice gates.

Sluice gate	Trung Trang	Van Uc 30 km	Van Uc 20 km	Lach Tray 40 km	Lach Tray 32 km	Lach Tray 24 km
R^2	0.93	0.87	0.82	0.79	0.81	0.78

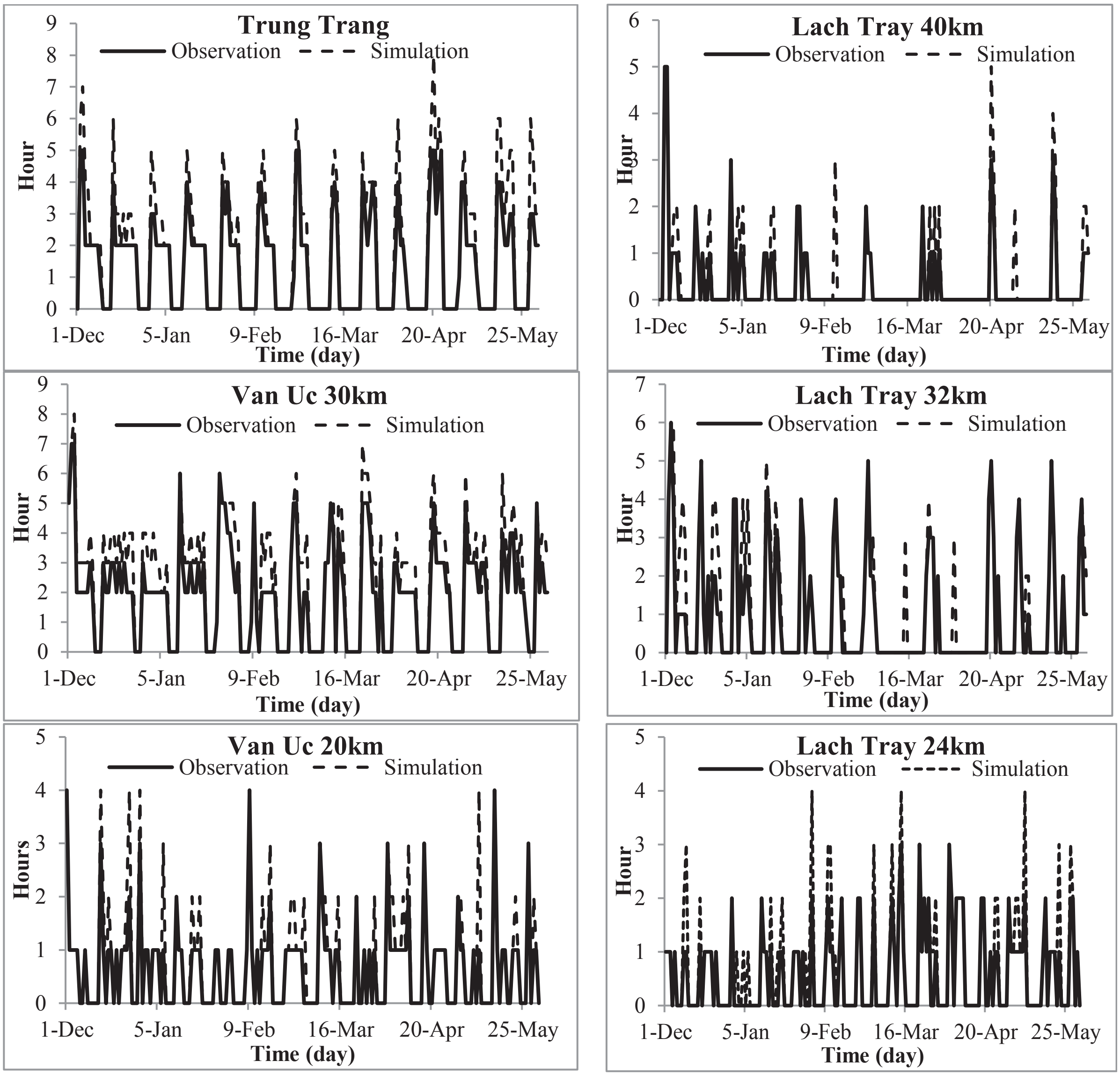

Fig. 8. Observed and simulated opening hours of sluice gates along the Van Uc and Lach Tray rivers.

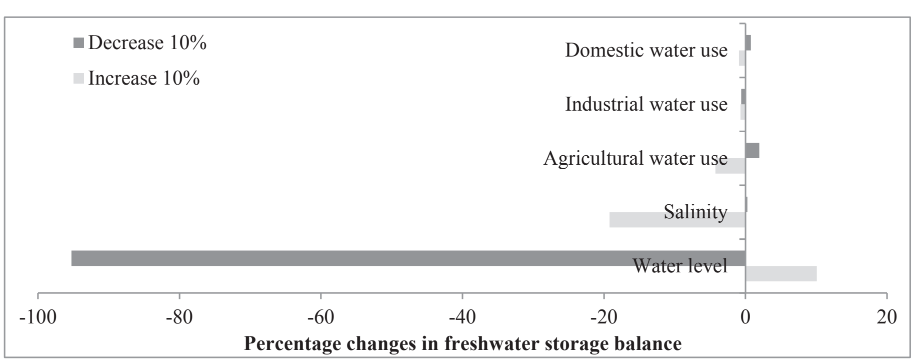

Fig. 9. Sensitivity analysis for freshwater storage balance in the system.

(Table 5). Relative sea level rise alongside upstream flow decline causes river water levels to increase significantly, leading to an increase in the opening hours for all sluice gates more than 24 km from the river mouths along the two rivers.

Freshwater for the Da Do River is provided by Trung Trang Sluice Gate which is about 40 km from the river mouth and the largest gate in the entire system (Table 1). Thus, under those scenarios which include relative sea level rise (i.e. Scenarios 4 and 5), opening

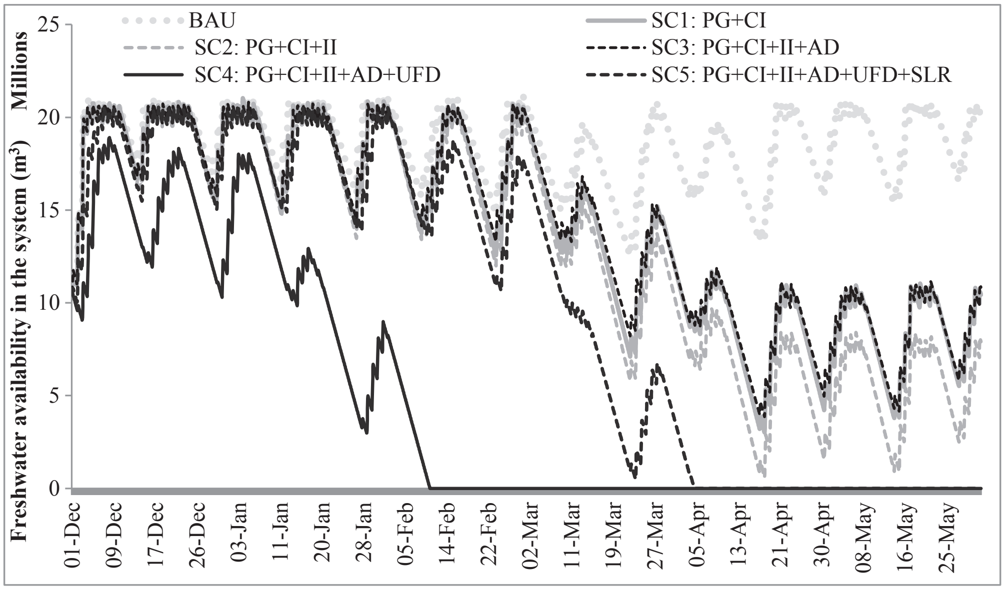

Fig. 10. Freshwater balance system in the dry season under BAU and future scenarios Legend: PG: Population growth, CI: Per capita use increase, II: Industrial use increase, UFD: Upstream flow decline, AD: Agriculture use decrease, SLR: Sea level rise; SC: Scenario.

hours of the crucially important Trung Trang sluice gate will not be reduced by increasing salinity, but on the contrary will increase substantially due to increased water levels on the supply side of the gate.

The opening of sluice gates between 20 km and 32 km, respectively, from the mouths of the Van Uc and Lach Tray rivers is regulated by both salinity and water level for BAU and under future scenarios (Table 5). However, opening of sluice gates located 40 km from the river mouths is regulated only by the water level condition. Under the UFD or UFD & SLR scenarios, salinity starts to decrease the opening hours of sluice gates located 30 km from the mouth of the Van Uc River and causes complete closure of sluice gates up to 32 km from the mouth of the Lach Tray River. These scenarios also result in complete closure for sluice gates located at 20 km or 24 km from mouths in both rivers (Table 5).

4.4. System vulnerability and salinity uncertainty analysis

The impacts of relative sea level rise and upstream flow decline on salinity at locations up the estuaries entails some uncertainty because detailed hydrological models of the Van Uc and Lach Tray estuaries are not available. An additional investigation was, therefore, undertaken to assess how the coastal freshwater system would be affected by further increases in salinity level. Under Scenario 5 (UFD & SLR) salinity was elevated by 1.3, 2.3, 3.3 and 3.9 times in both rivers to assess whether higher salinity levels would cause complete closure of sluice gates more than 30 km from the mouth of the Van Uc and 40 km from the mouth of the Lach Tray.

Simulations indicate that when salinity predicted under UFD & SLR is increased by a factor of 1.3 times, sluice gates at 30 km from the mouth of Van Uc River will be closed completely, resulting a

Table 5
Number of hours when water level is high enough and salinity is low enough for opening of sluice gates along the Van Uc and Lach Tray rivers under different scenarios.

Van Uc	Location	40 km from river mouth				30 km from river mouth				20 km from river mouth			
	Scenario	BAU	UFD	SLR	UFD&SLR	BAU	UFD	SLR	UFD&SLR	BAU	UFD	SLR	UFD&SLR
	Water level high enough for opening gates (hours)	495	182	932	495	777	495	1277	932	777	495	1277	932
	Salinity low enough for opening gates (hours)	4368	4368	4368	4368	4360	4296	4296	4093	3739	3272	3272	2671
	Combined water level and salinity conditions appropriate for opening gates (hours)	495	182	932	495	769	423	1205	657	148	0	132	0
Lach Tray	Location	40 km from river mouth				32 km from river mouth				24 km from river mouth			
	Scenario	BAU	UFD	SLR	UFD&SLR	BAU	UFD	SLR	UFD&SLR	BAU	UFD	SLR	UFD&SLR
	Water level high enough for opening gates (hours)	182	118	495	374	374	118	777	374	629	275	1096	629
	Salinity low enough for opening gates (hours)	4368	4368	4368	4368	4330	4186	4186	3873	3873	3436	3436	2884
	Combined water level and salinity conditions appropriate for opening gates (hours)	182	118	495	374	336	0	595	0	134	0	123	0

Legend: BAU = Business as usual, UFD = Upstream flow decline, SLR = Sea level rise, UFD & SLR = Combined upstream flow decline and sea level rise. A total of 4368 h were simulated.

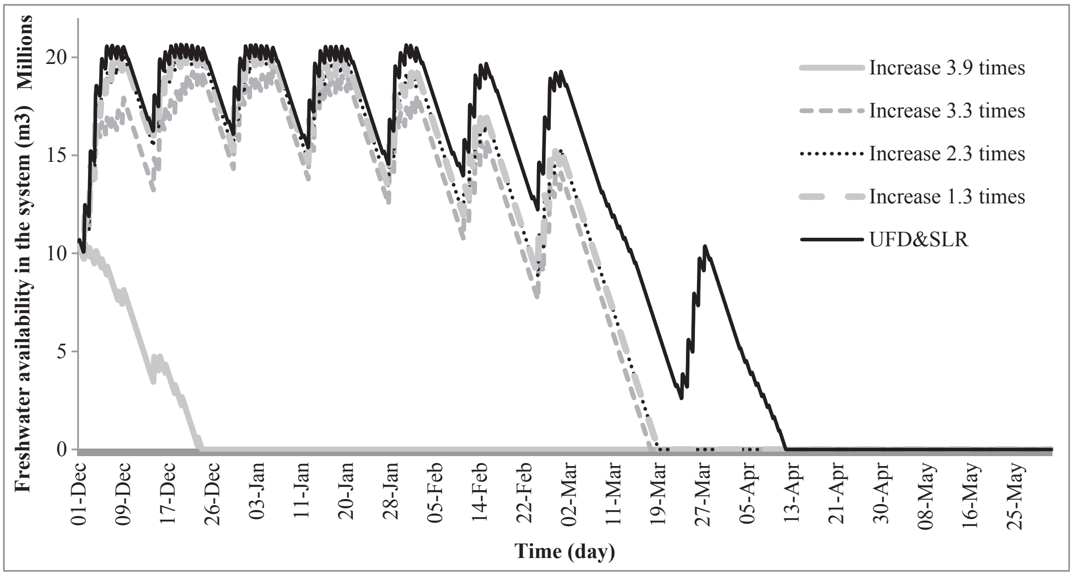

Fig. 11. Behavior of the freshwater balance system under elevated salinity increases.

further collapse for the system in the latter months of the dry season (Fig. 11). However, sluice gates at 40 km from the mouths of the Lach Tray and Van Uc can still open until salinity levels are increased by factors of 3.3 times and 3.9 times, respectively, above the levels predicted under UFD & SLR. Permanent closure of the very high capacity sluice gate at Trung Trang, 40 km from the mouth of the Van Uc River causes complete collapse of the system (Fig. 11). Permanent closure of all sluice gates on the Lach Tray is not as damaging as permanent closure of the Trung Trang gate, but still results in significant under supply of water during the latter half of the dry season (Fig. 11).

5. Discussion

Climate change and socio-economic development can both be expected to present major on-going challenges for the management of water resource systems, particularly in coastal urban settings (Ross et al., 2015). Socio-demographic factors such as changes in population size, increasing per capita water usage and land conversion (typically from agricultural to industrial or residential uses) are very likely to affect water demand (DONRE, 2015; Sun et al., 2017). Changes in seasonal precipitation and sea level rise are expected to affect water supply (Ross et al., 2015), whereas other climatic factors such as changing temperatures could plausibly affect supply and demand simultaneously (Dawadi and Ahmad, 2013). Altered seasonal precipitation patterns and rising sea levels can therefore be expected to significantly influence the dynamics and complexity of managing coastal freshwater systems, often via impacts on patterns of river flows as well as the frequency, duration and extent of marine-derived saline water penetration in estuaries (Etemad-Shahidi et al., 2015; Zhou et al., 2017).

Upstream flow decline significantly affects water availability of the coastal freshwater system in the Da Do Basin. Upstream flow reductions could be driven by climate change, especially a gradual decrease in precipitation (Etemad-Shahidi et al., 2015), coupled with increased temperature (Dawadi and Ahmad, 2013). Significantly, over the past 57 years, precipitation has decreased (Fig. 3) and air temperatures have increased (Fig. 4) in the Hai Phong region and in its upstream catchment, and these trends are projected to continue over the next 50 years (MONRE, 2016), further reducing river flows in the Da Do Basin. Flow reductions will also be exacerbated by human activities altering flow regimes. Three dams (Lai Chau, Son La and Hoa Binh) for hydropower are located upstream of Hai Phong City, and the operational management of these dams can significantly influence river flows in the Hai Phong region, especially during the dry season (DONRE, 2015). These hydropower dams usually lack water in the dry season due to low precipitation and also because water is retained by China's dams further upstream, thereby reducing water flows in downstream regions (Urban et al., 2017). Water releases from these dams for electricity generation are not coordinated with operational requirements of Hai Phong's freshwater supply system, missing an opportunity to use appropriately timed releases to elevate water level and reduce salinity on the supply side of Hai Phong's sluice gates (DONRE, 2015). These hydrological changes, coupled with anticipated sea level rise, can be expected to result in altered spatial and temporal patterns of river discharge, water levels and salinity penetration in the estuaries. In recent years, the Da Do Basin has witnessed a high level of salinity (>3.0 ppt) occurring in the lower parts of the Van Uc and Lach Tray estuaries (Pham, 2014), with significant risk of major decline in the quantity and quality of water available for urban, industrial and agricultural uses (DONRE, 2015).

In this study, SD model simulations predict that the length and level of salinity penetration in the Da Do Basin system will increase significantly over coming decades in response to relative sea level rise and upstream flow decline. Our SD model also indicates that upstream flow decline is a more influential driver of salinity penetration than sea level rise and tidal level. A relative sea level rise of 30 cm is predicted to increase salinity by 25% and 30% at 40 km from the mouths of the Van Uc and Lach Tray rivers, but these salinity increases more than double when upstream flow decline is included in addition to relative sea level rise. These results are consistent with other studies which apply different methods in related settings. Zhou et al. (2017), for instance, applied Bayesian neural networks to investigate the relationships between streamflow, sea level and tidal level on salinity intrusion in the Pearl River in China, also finding that upstream flow decline led to a decrease in water level and an increase in salinity. Similarly, Etemad-Shahidi et al. (2015), applying a one-dimensional hydrodynamic model to understand the interactions between sea level rise and tidal level on salinity in Bahmanshir estuary in Iran, also identified the significance of upstream flow reductions driven by

climate change through a gradual decrease in precipitation.

Although hydrodynamic models and Bayesian neural networks can predict more precisely the impacts of sea level rise and upstream flow decline on water level and salinity (Etemad-Shahidi et al., 2015; Zhou et al., 2017), the modeling approach presented here offers several advantages for the planning and management of water resource systems. In this study, regression models were combined with SD models to help decision-makers investigate future interactions among influential factors beyond the limits of available data. More specifically, correlation and regression approaches were used to extrapolate SD parameterization beyond existing data to investigate the future influences of interactions between upstream flow decline and relative sea level rise on salinity, water level, sluice gate operation and freshwater balance. Regression-based extrapolations of existing data have been applied in SD models elsewhere, for example to forecast the impacts of various factors on the diffusion of eco-innovations (Vīgants et al., 2016) and to forecast the quantity and composition of solid waste (Vivekananda and Nema, 2014).

Furthermore, SD models have been shown to be an excellent strategic water management modeling tool since they provide an understanding of the dynamic and complex challenge of managing water supply and demand systems subject to multiple interactions (Sahin et al., 2017; Winz et al., 2009). Numerous biophysical and socio-economic scenarios can be incorporated into one comprehensive SD model and analyzed via an adjustable dashboard display (Sahin et al., 2015) to help decision makers understand the behavior of a complex system. For example, our SD model predicts that sea level rise acts to increase the volume of freshwater that can be supplied through sluice gates in the upper reaches of the estuaries as precipitation declines. Heightened sea levels hold back dwindling upstream flows and increase water levels on the supply side of the sluice gates whilst-crucially-salinity still remains below the 1 ppt threshold, enabling sluice gates to still be opened. As a consequence, under this combination of interacting drivers, sluice gates in the upper estuaries can be opened for more hours and the freshwater supply demand balance can be maintained for longer during the dry season. The Da Do Basin system is somewhat unusual because its topography is particularly flat, its main freshwater intake is located at 40 km from the river mouth, and freshwater is conveyed to the lower basin through the natural infrastructure of the Da Do River and irrigation channels. There may, however, be other situations in which water managers could potentially use this beneficial effect of sea level rise to counteract decreases in river flows by re-locating main intakes further up river. This unexpected beneficial impact of sea level rise only becomes evident because the SD model is able to capture interactions between key drivers – in this case upstream flow decline and sea level rise.

In addition, the relative unimportance of demand side drivers in affecting vulnerabilities in the case study system is somewhat surprising, particularly given the high rate of population growth and rapid pace of land use change. The reason is that irrigation-intensive agriculture currently accounts for 83% of total water consumption in the basin (DONRE, 2015), and thus an annual decrease of 0.5% in future agricultural water demand counteracts the effects of increasing affluence and expanding population. The ability of the SD model to address supply and demand drivers simultaneously is clearly a major advantage for modeling future management, as rapid identification of the likely scale of vulnerabilities on the two sides of the system is helpful for making best use of available resources for adaptation planning.

Stakeholder involvement in the development and validation of the SD model was an important part of the process as it ensured that the model provided an appropriate representation of real world conditions by incorporating stakeholders' experience and knowledge of system behavior and system management. Once the model's validity had been established it was used to facilitate stakeholder discussions about appropriate adaptation options for securing the balance between supply and demand in the system under climate change against a background of an expanding population and anticipated changes in industrial and agricultural production. Sensitivity analyses from the SD model focused stakeholders' attention on potential adaptation options for augmenting dry season water supply as simulation modeling clearly identified supply shortages during the dry season under future climate change as the primary vulnerability in this system. Stakeholders suggested that pumping stations could be constructed at appropriate locations in the upper estuaries to extend the length of time during each tide cycle when freshwater could be sourced into the Da Do River and irrigation channels. Predictions from the SD model identified the key vulnerability (water supply shortage during the dry season, driven primarily by upstream flow decline) and stakeholders' acceptance of the model's validity (gained through stakeholder participation in model development and testing) enabled the SD model to be used effectively as a tool to facilitate discussions about appropriate adaptation interventions at particular locations. Used in this way, an SD model calibrated using readily available historical data and incorporating stakeholder expertise quickly identified that adaptation effort could be applied to improve coastal freshwater management.

During past decades, water resource management has focused mainly on assessing water supply or water demand separately (Dawadi and Ahmad, 2013). Consequently, the many interactions and relationships between hydrological and socio-economic aspects of water resource systems have rarely been taken into account (Qin et al., 2011), especially with respect to analyzing long-term scenarios regarding these interactions. Such disjointed analyses could, inadvertently, result in inappropriate and/or unsustainable decisions regarding water resource management. More recently, researchers have incorporated climate change scenarios into SD models to assess water supply and demand simultaneously (e.g. Dawadi and Ahmad, 2013; Sun et al., 2017; Sušnik et al., 2013). However, there remains a paucity of knowledge with regard to understanding the multiple interactions and relationships among sea level rise, upstream flow regimes, estuarine salinities, population growth and socio-economic development, and their combined effects on the vulnerability of coastal freshwater management systems. The current study provides a first attempt to demonstrate the efficacy of SD modeling for assessing the vulnerability of a coastal freshwater system in a developing country by investigating all of these factors and their interactions concurrently. The modeling approach presented here and the key finding regarding the significance of upstream flow decline, are likely to be highly applicable to other basins in Hai Phong City, as well as in estuarine settings in both developing and developed coastal cities where water resource management is vulnerable to sea level rise and upstream flow decline, alongside pressures from socio-economic development.

6. Conclusion

This paper presents a feedback-driven SD model that simulates dynamic balance of the supply and demand sides of a coastal freshwater system in Da Do Basin, Vietnam during the dry season. Simulations from the SD model indicate that current freshwater availability in the system is sufficient to supply for domestic, industrial and agricultural water demands. However, modeling suggests that the system can collapse under several plausible future scenarios. Future projections identified decrease in upstream flows as the most influential driver of the system's dry season vulnerability. Upstream flow decline spatially and temporally decreased

opening hours of all sluice gates along the estuaries from which freshwater is sourced, and forced complete closure of sluice gates in the system's lower reaches, rendering the system incapable of satisfying demand during the latter months of the dry season. The SD model can be used as a decision support tool to improve understanding of the dynamic behaviors of the system, to assess potential vulnerabilities under plausible future scenarios, and to identify potential adaptation options for securing the system against those vulnerabilities.

This research has shown that SD can be a useful tool for integrated participatory appraisal of coastal freshwater systems, incorporating climatic drivers (sea level rise and upstream flow decrease) and socio-economic development (population growth, changes in industrial and agricultural productions). Modeling results can be used to assess and quantify potential climatic and socio-economic influences on the vulnerability of the system. Such integrated modeling is very rarely applied in water resources research currently, and this work thus represents an early attempt to address this research gap for coastal regions of developing countries. The modeling approach and findings from this study could be applicable to both developing and developed coastal regions where water resource management is vulnerable to interacting challenges from climate change and socio-economic development.

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Appendix A. Applications of system dynamics modeling in water supply and demand system

No	Authors	Country	Supply side		Demand side	Climate change consideration	Participatory
			Hydrological component	Physical component			
1	Dawadi and Ahmad (2013)	United States	Surface water	Reservoir	Residents, industry	Temperature	No
2	Gohari et al. (2013)	Iran	Surface water, groundwater		Residents, industry, agriculture	No	No
3	Qin et al. (2011)	China	Surface water	Wastewater plant	Residents, industry	No	No
4	Sahin et al. (2015)	Australia	Surface water	Reservoir, desalination plant	Residents	No	Yes
5	Sahin et al. (2017)	Australia	Surface water, ground water	Reservoir, desalination plant	Residents	No	Yes
6	Scarborough et al. (2015)	Australia	Groundwater	Reservoir, desalination plant, recycled water plant	Residents	Temperature	No
7	Sun et al. (2017)	China	Surface water		Residents, industry, ecology	No	No
8	Sušnik et al. (2012)	Tunisia	Surface water, groundwater		Residents, industry, agriculture	Temperature	Yes
9	Sušnik et al. (2013)	Egypt	Surface water		Residents, industry, agriculture	Sea level rise	No

Appendix B. Correlation coefficient values for the changes in salinity (ppt) and water level (cm) corresponding to an increase 1 cm in tide level

Van Uc River	Location	Estimated Coefficient	Adjusted R^2	p value	F statistic	Standardized residuals		
						Max	Min	Range % (-1 to 1)
	Salinity							
	40 km	0.00074	0.89	≤0.0001	35627	3.73	- 1.32	67.03
	30 km	0.00276	0.85	≤0.0001	25063	3.22	−0.97	78.43
	20 km	0.00566	0.61	≤0.0001	6923	4.52	−0.98	89.02
	Water level							
	40 km	0.624	0.64	≤0.0001	7888	2.39	−3.13	63.66
	30 km	0.700	0.75	≤0.0001	12889	2.41	−3.16	65.49
	20 km	0.776	0.82	≤0.0001	19767	2.83	−3.27	66.11
Lach Tray River	Salinity							
	40 km	0.00079	0.92	≤0.0001	47684	4.14	−1.27	70.06
	32 km	0.00313	0.87	≤0.0001	28733	3.38	−1.00	75.08
	24 km	0.00528	0.70	≤0.0001	10053	3.85	−0.83	84.43
	Water level							
	40 km	0.658	0.59	≤0.0001	6197	2.43	−3.58	64.90
	32 km	0.696	0.64	≤0.0001	7846	2.40	−3.65	65.3
	24 km	0.772	0.74	≤0.0001	12336	2.39	−3.77	65.27

Appendix C. : Correlations between upstream flow declines and water level and salinity

Correlations between water level and salinity at six locations along the Van Uc and Lach Tray rivers, and tide level at Hon Dau Station were quantified separately for upper tide level (tide ≥ 170 cm), lower tide level (tide <170 cm), and for the whole tide level. These correlations were calculated for different distances from the river mouths (Table C1).

more than 60 cm in the Lach Tray River and at more than 113 cm in the Van Uc River (Figs. C1 and C2). This is because upstream flows contribute to these water levels. Consequently, upper cycles water levels appear to be more strongly controlled by tide level while, lower cycle water levels are more strongly controlled by upstream flows. Although upper cycle water levels are more tightly coupled with tide level, they are also partially influenced by upstream flow. The Van Uc is larger than the Lach Tray, and thus receives more upstream flows. Consequently, lower cycle water levels of the Van

Table C1
Partial correlations between tide level and water level and salinity at different locations from the river mouths.

Van Uc River	Location	40km			30km			20km		
	Variable	Tide (cm)			Tide (cm)			Tide (cm)		
		<170	whole	≥170	<170	whole	≥170	<170	whole	≥170
	Water level	0.254	0.802	0.724	0.362	0.864	0.800	0.467	0.905	0.856
	Salinity	0.526	0.945	0.938	0.821	0.924	0.947	0.834	0.798	0.975
Lach Tray River	Location	40km			32km			24km		
	Variable	Tide (cm)			Tide (cm)			Tide (cm)		
		<170	whole	≥170	<170	whole	≥170	<170	whole	≥170
	Water level	0.265	0.766	0.663	0.311	0.802	0.704	0.405	0.859	0.778
	Salinity	0.684	0.957	0.972	0.879	0.931	0.973	0.935	0.844	0.997

Correlation analysis identified strong correlations between river water level and tide level, even 40 km upstream from the river mouths (Table C1 and Figs. C1 and C2). The strength of this correlation varies with tide level. River water level tracks tide level closely during the upper half of the tide cycle, whereas river water level and tide level differ more during the lower half of the tide cycle (Table C1 and Figs. C1 and C2). Although tide level drops to 30 cm, water levels at 40 km from the river mouths still remain at

Uc are higher than the Lach Tray (Figs. C1 and C2). On the basis of this correlation analysis, future scenarios in the simulations which include reductions in upstream flow use upper cycle water levels and lower cycle water levels which are decreased by 15 cm and 30 cm, respectively, from current for the Van Uc River, and are decreased by 10 cm and 30 cm, respectively, from current for the Lach Tray River.

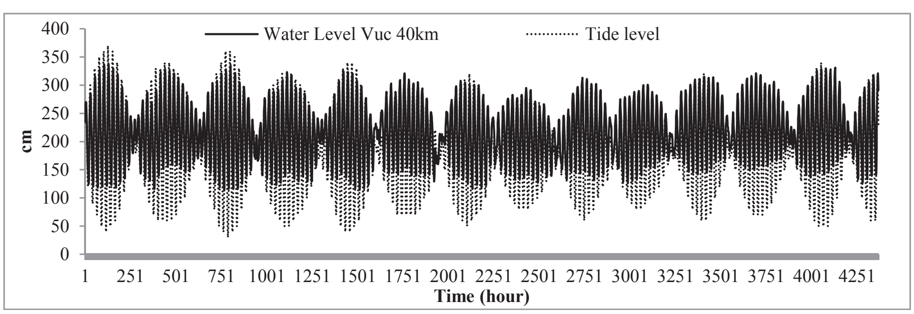

Fig. C1. Relationship between tide level and water level at 40 km from the mouth of the Van Uc River.

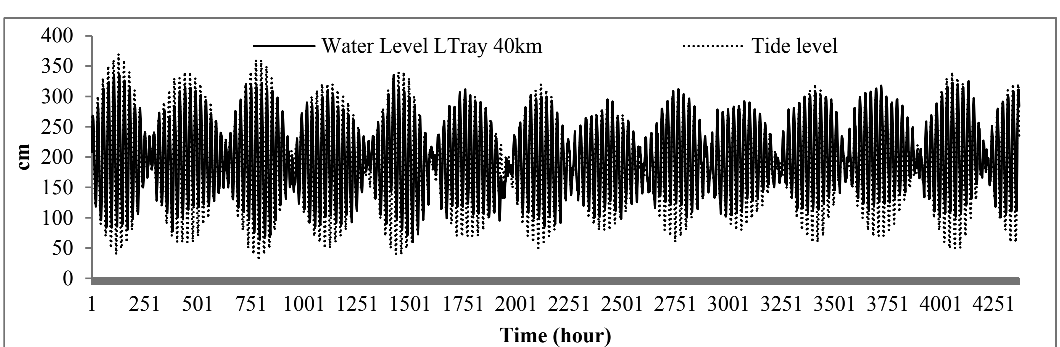

Fig. C2. Relationship between tide level and water level at 40kmfrom the mouth of Lach Tray River.

Tide level and salinity are also strongly correlated (Table C1) with particularly strong correlations during the upper tide cycle. The correlation between tide level and salinity in the Lach Tray is stronger than in the Van Uc because the Lach Tray receives less freshwater from upstream. Thus, salinity in the Lach Tray is particularly strongly controlled by tide level. A decrease of 30 cm in lower cycle water levels in the Van Uc and Lach Tray rivers will result in backflow occurring sooner in the tide cycle. For example, backflows at Trung Trang Station, which is about 38 km from the mouth of the Van Uc, currently start to occur once tide level reaches flows. Under this scenario we assume that a reduction of 30 cm in river water level will allow backflow to occur at a correspondingly lower tide level (at 140 cm instead of 170 cm at Trung Trang Station), causing salinity to begin to increase at a lower tide level. These relationships are used to assess the influence of upstream flow decline on salinity and water level along the Van Uc and Lach Tray rivers.

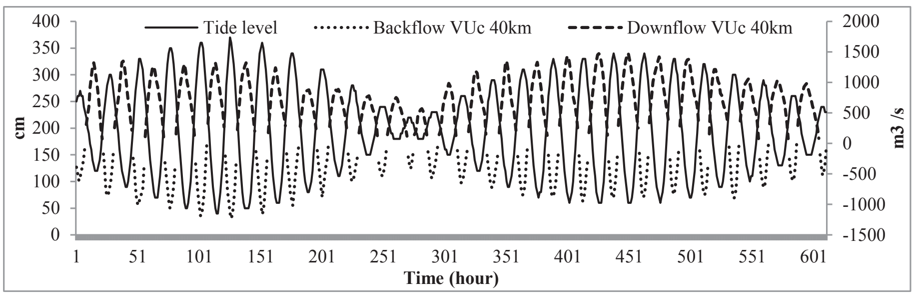

Fig. C3. Relationship between tide level and backflows, downflows.

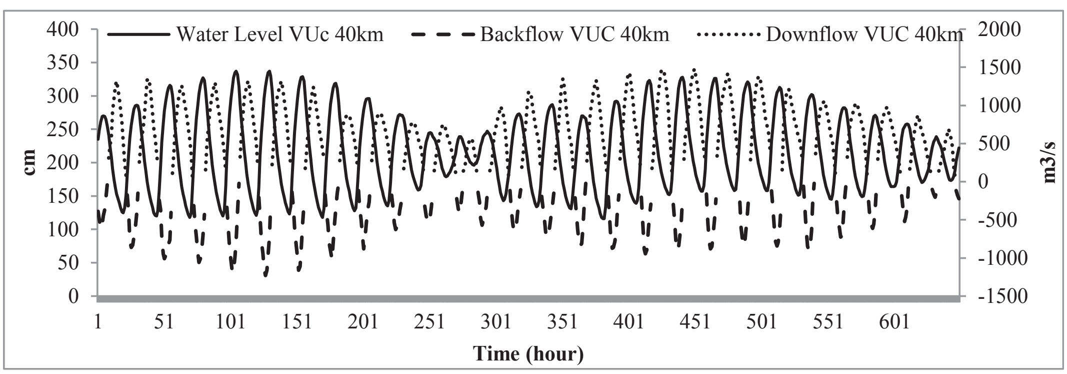

Fig. C4. Relationship between river flows and water levels.

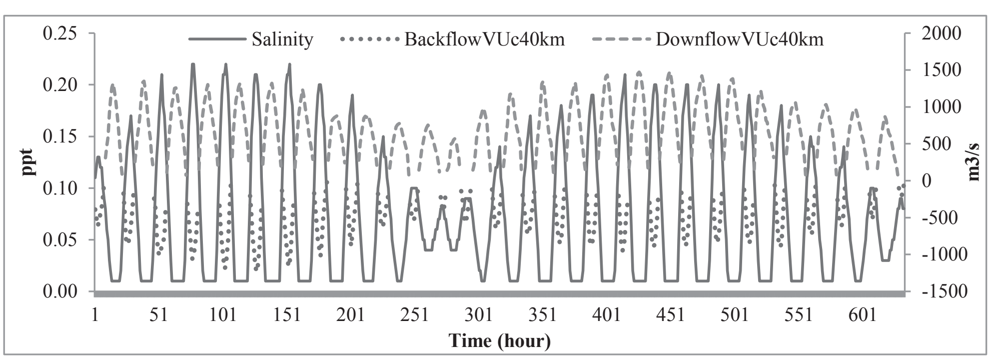

Fig. C5. Relationship between river flows and salinity.

170 cm and water level is at 144 cm (Figs. C3 & C4). Backflows are currently equal to downflows at Trung Trang Station once tide level is 200 cm and water level is 160 cm. The backflows will happen sooner when lower cycle water levels along the Van Uc and Lach Tray rivers decrease. Salinity rises rapidly once backflow begins (Fig. C5). Consequently, salinity will also be higher when water levels along these rivers decrease following a decrease in upstream

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